

Research Article

Thermal Energy Consumption Assessment in a Fluid Milk Plant

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Abstract: The main energy conservation opportunities in a dairy plant are in refrigeration, and steam generation. This paper aims to identify potential energy and water savings and opportunities to improve the thermal efficiency of a fluid milk processing plant, using energy analysis and Heat Integration methods. Methodologies for energy analysis and Pinch Analysis with the use of HENSAD and Aspen Energy Analyzer are applied. The main specific energy consumptions are defined as indicators of the progress of improved energy efficiency. The determination of energy performance indicators and energy targets of the heat exchanger network, as well as its design, allowed identifying opportunities for improvement to reduce fuel and water consumption through heat recovery in the milk pasteurization process. Current hot and cold utilities duties are satisfied, for a minimum allowable temperature difference of 20 °C. Total annual savings of 60 t of fuel oil and 15,800 m³ of water allow assessing the feasibility of an investment project for improved heat recovery.

Keywords: Heat Recovery, Heat Integration, Pinch Analysis, Pasteurization**How to cite this paper:**

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1. Introduction

Among the food industries, the dairy industry is one of the most important sensitive one [1]. The introduction of energy management in dairy factories is necessary to save energy in a cheap, controlled and planned way.

There is a wide range of technologies and process integration opportunities available for achieving these objectives, including decreasing fossil fuel and electricity demand by increasing heat integration within individual processes and across the total cluster site [2].

The greatest heat requirements for liquid milk production are for pasteurisation and cleaning in place. This paper aims to identify potential energy and water savings and opportunities to improve the thermal efficiency of a fluid milk processing plant, using energy analysis and Heat Integration methods. This powerful methodology has since been extended to a wide range of applications, such as Mass Integration, Carbon Management and Financial Pinch Analysis [3]. The procedure applied in this study helps to meet important energy-related social and economic problems, still unresolved.

The assessment of the energy analysis and integration results contribute to the better identification of the potentialities for energy recovery in dairy plants. Fuel and water savings, associated to heat recovery in the industry under study justify investment projects based on heat exchanger network retrofit.

By applying a heat exchanger network retrofit, it is also designed an improved heat exchanger network without thermodynamic violations, frequently observed in industrial processes.

Application of energy analysis followed by Heat Integration methods in a single dairy process, allowed assessing energy performance and the feasibility for integrating all the dairy plant sub processes, which is considered the novelty of this study.

2. Literature Review

Efficient use of energy is an imperative need for competitiveness and profitability enhancement in the process industries [4]. The energy auditing could be a useful method and for milk dairy processes, by energy auditing technique the waste energy can be reduced and the system efficiency can be increased [5,6]. Dairy industry uses electrical energy and thermal energy as main energy source [7]. A lot of awareness has been generated in the conducting energy audits to achieve energy conservation [8]. Energy conservation will help to reduce the energy costs which will reduce the processing costs [9]. Waheed [10] reported that pasteurization is the most energy-intensive unit operation in the processing of orange juice. Ramirez [11] called it the most common thermal process in the dairy industry

Currently, a large amount of the thermal energy used in the chemical industry is not recovered (by process - process stream heat exchange), but removed as low grade waste heat that ends up released into the environment [12, 13]. Pasteurization is the first stage of most dairy processes [14]. The adequacy and quality of the proposed solutions depend on selecting the right data set, which captures all relevant heating and cooling demands of the considered process [15].

Since the beginning of the century, Pinch Analysis (PA) methodologies have been extended to handle various production planning problems [16]. Incorporating fundamentals of thermodynamics, PA was initiated as a conceptual optimization method for energy conservation in process industries [17, 18]. PA, for more comprehensive information, is mainly operated through graphical and numerical tools to target the maximum energy recovery plan for heat exchanger network (HEN) synthesis and retrofit [19]. PA was introduced for the design of HEN to maximize process heat recovery and minimize utility requirements using the minimum temperature approach (ΔT_{min}) as a key decision variable. Designers typically perform capital-energy trade-off from the relationship between ΔT_{min} , utility, and capital costs before selecting the optimum ΔT_{min} for grassroots HEN design [20].

In process industries, process integration strategies that include thermal systems provide resources to reduce energy use and environmental emissions. HEN retrofit is an effective way to utilise heat from process streams and to minimise the energy consumption [21] and synthesis of HENs is widely recognized as one of the most energy-saving techniques in the process industry [22]. Bagajewicz [23] proposes an interactive process/pinch analysis scheme to determine energy retrofit horizons. The term "horizon" is used to indicate the maximum amount of energy of a pre-established temperature level that one can recover by varying operating conditions on a fixed flowsheet. Since energy management is an important means by which to improve energy efficiency, the use of specific energy consumption (SEC) to identify potential improvements in energy efficiency is seen as an important instrument of energy management [24]. Brush [25] reports an energy intensity of 214 kJ/kg for steam in the liquid milk pasteurization process in typical US facilities, although it may not be representative in other facilities. Regardless of the convenience of using the SEC, it is difficult to attribute part of the total energy consumption to one of the products.

In this case the industry does not have a defined energy baseline, built on the basis of the measurement of the consumption of primary energies or specific energy carriers for each dairy product. Only the analysis of energy use will allow defining the specific consumptions (t steam/t milk, MJ/t milk, t Fuel Oil/t milk) of the pasteurized fluid milk manufacturing process and the measurement of energy performance.

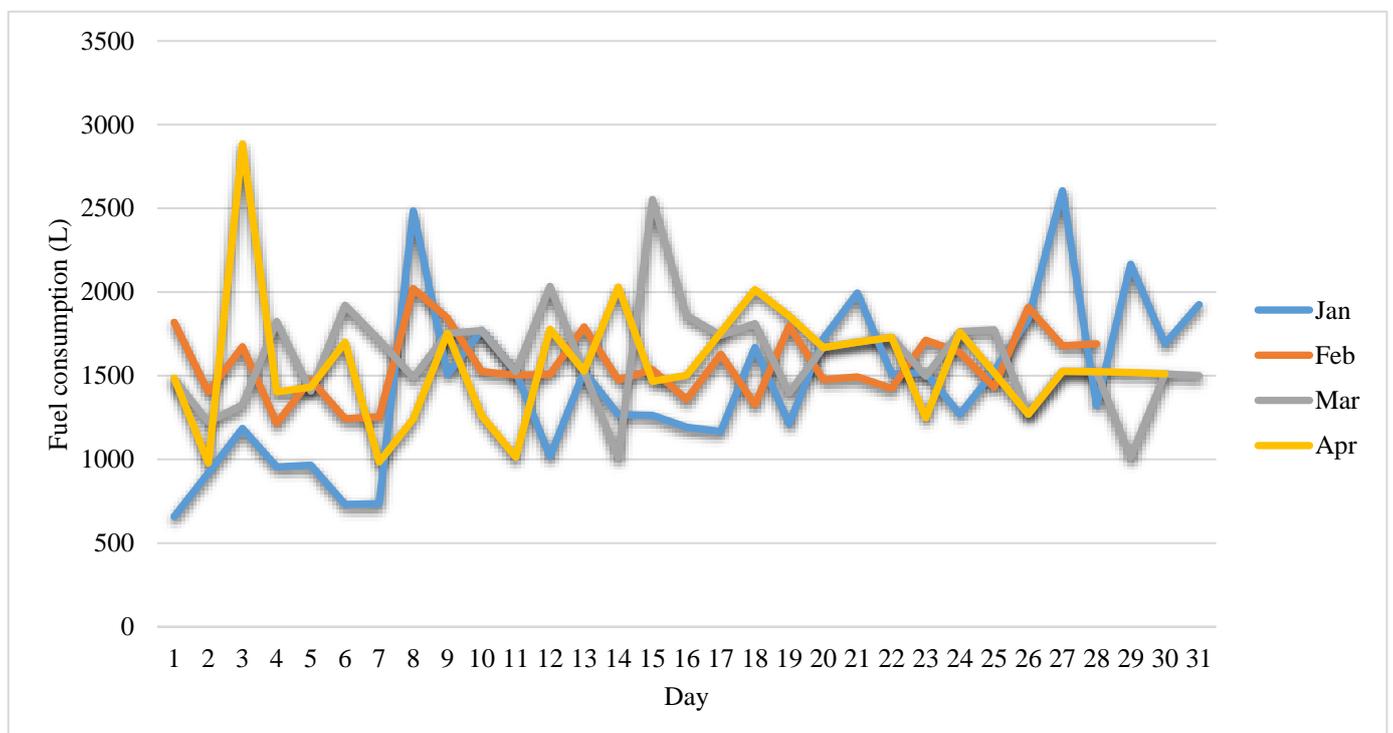
3. Research Methodology

3.1. Methodologies and software

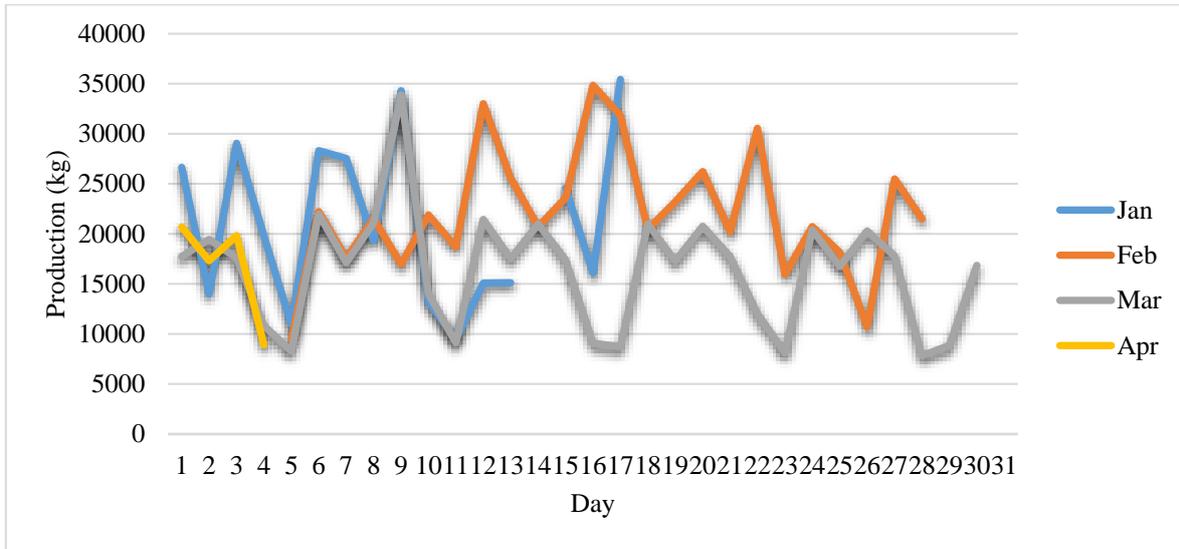
The energy assessment in the milk process is based on the implementation of the energy review activities according to the Cuban standard ISO 50001: 2019 with the aim of determining the energy performance indicators by applying energy balance and Heat Integration methodologies in the pasteurized fluid milk process. In the HEN analysis and design, Pinch Analysis methodology is applied to determine network targets, minimum optimum temperature difference, minimum number of heat exchange units and the maximum energy recovery (MER) [26]. Data processing for Heat Integration was performed by HENSAD [27] and Aspen Energy Analyzer [28]. The main activities carried out in the energy review were: (1) analysis of energy use and consumption, (2) determination of current energy performance, (3) identification of opportunities to improve energy performance.

3.2. Analysis of use and consumption of energy in the pasteurized fluid milk process

The dairy plant produces pasteurized fluid milk, cheese, yogurt, soy yogurt, and ice cream. The cooling water service consists of three ice banks of 22.5 m³ each, two compressors of 90 kW and one of 62 kW. The steam service consists of three water-tube boilers with steam generation capacities of 1.5, 2.5 and 4.5 t/h, which consume Fuel Oil. The saturated steam pressure for process is 0.35 - 0.6 MPa. The registration and analysis of the operating reports corresponded to the fuel consumption for each product produced in the first four months of 2018 as reference year, from which the plant began a modernization process. Figure 1a shows overall fuel consumption and Figure 1b pasteurized milk production for all processes in the plant, although energy analysis is performed only for fluid pasteurized milk.



(a)



(b)

Figure 1. (a) Fuel consumption and (b) Pasteurized milk production.

4. Results and Discussion

4.1. Determination of current energy performance

Energy performance is measured by determining the duties for heating and cooling services in the fluid milk process. The heating service (steam consumption) duty in the water heater (m_s), expressed in kg/s, is determined by equation (1).

$$m_s \cdot \Delta H_{VAP} = m_w \cdot C_{p_w} \cdot (T_{f_{fw}} - T_{i_{fw}}). \quad (1)$$

The hot water flow (m_w) is determined by equation (2)

$$m_{rm} \cdot C_{p_{rm}} \cdot (T_{f_{rm}} - T_{i_{rm}}) = m_w \cdot C_{p_w} \cdot (T_{f_{hw}} - T_{i_{hw}}). \quad (2)$$

The cooling service duty is constituted by cooling water consumption in milk reception (m_{cwr}), given by equation (3) and cooling water consumption in pasteurization (m_{cwp}), given by equation (4)

$$m_{lc} \cdot C_{p_{lc}} \cdot (T_{i_{lc}} - T_{f_{lc}}) = m_{cwr} \cdot C_{p_w} \cdot (T_{f_{cwr}} - T_{i_{cwr}}). \quad (3)$$

$$m_{pm} \cdot C_{p_{pm}} \cdot (T_{i_{pm}} - T_{f_{pm}}) = m_{cwp} \cdot C_{p_w} \cdot (T_{f_{cwp}} - T_{i_{cwp}}). \quad (4)$$

Nomenclature: ΔH_{VAP} = latent heat of vaporization of water (kJ/kg), C_{p_w} = specific heat capacity of water (kJ/kg °C), $T_{f_{fw}}$ = final temperature of fresh water (°C), $T_{i_{fw}}$ = initial temperature of fresh water, m_{rm} = raw milk flowrate (kg/s), $C_{p_{rm}}$ = specific heat capacity of raw milk, $T_{f_{rm}}$ = final temperature of raw milk, $T_{i_{rm}}$ = initial temperature of raw milk, m_w = water flowrate, $T_{i_{hw}}$ = initial temperature of hot water, $T_{f_{hw}}$ = final temperature of hot water, m_{cwr} = water flowrate for cooling in milk reception, $T_{f_{cwr}}$ =

Heat integration is an important part of Process Integration (PI), for which data extraction has a crucial significance [28]. The streams considered in the analysis are raw milk (H1), hot milk (H2), refrigerated milk (C1), pasteurized milk (C2), hot water (C3). Utilities are steam service (S) and refrigerated water (CW).

Table 2. Stream data.

Stream	m (kg/h)	cp (kJ/kg°C)	CP=m·cp (kJ/h°C)	Ti (°C)	Tf (°C)	ΔH (kJ/h)
H1	5,256	3.93	20,656	27	7	413,122
H2	5,256	3.93	20,656	78	6	1,487,238
C1	5,256	3.93	20,656	7	32	516,402
C2	5,256	3.93	20,656	32	78	950,180
C3	7,200	4.19	30,170	28	85	1,719,576

The global minimum temperature difference (ΔT_{\min}) in this case is set at 20 °C as initial assumption, since current average temperature difference at the cold end in the heat exchanger units is 20 °C. This is a multiple pinches case, where there are two Pinch points, one at 48 °C and 28 °C and the other at 27 °C and 7 °C.

The minimum hot and cold duties are 592.5 kW and 235.25 kW. Current hot and cold utilities duties are satisfied, for a minimum allowable temperature difference of 20 °C. These results define a well-conceived HEN design. The Composite Curves diagram (Figure 3) shows the minimum energy targets (hot and cold duties). There is an energy potential of 292.83 kW, feasible to be recovered (MER) through heat exchange between process streams, which is obtained from the difference between the accumulated available energy of the hot composite curve (528 kW), shown in Table 2 and the minimum cooling duty.

Current cold utility duty is 68.33 % higher than the minimum cold utility requirement, while the current hot utility is lower than the hot utility target.

This behavior is typical, because in continuous pasteurization the hot and cold milk exchange heat and only a small additional utility load is required.

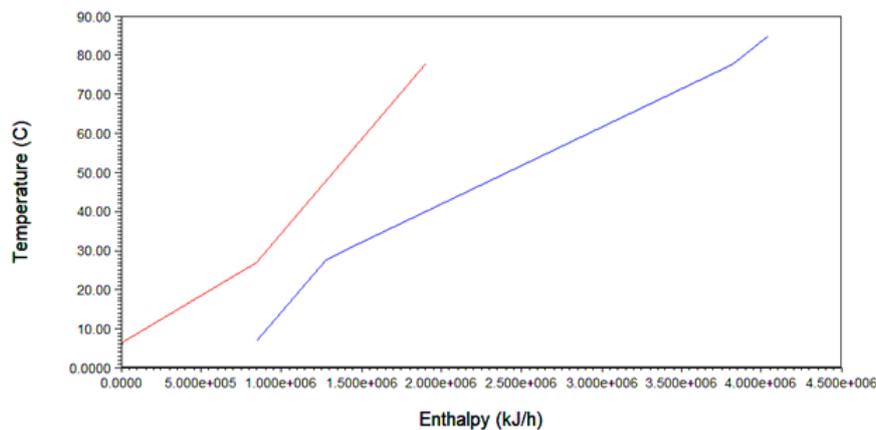


Figure 3. Composite curves diagram.

Table 3. ΔT_{\min} Sensitivity analysis.

ΔT_{\min} °C	Exch. Area m ²	Hot Util. Load kJ/h	Cold Util. Load kJ/h	EAO (1,000) \$/y	Number of Exchangers
5.000	138.54	1,822,680	536,760	172.1	7
7.500	121.92	1,874,160	588,600	174.4	7
10.00	11.75	1,926,000	640,080	173.3	7

12.50	104.95	1,977,480	691,920	180.7	7
15.00	100.22	2,029,320	743,400	184.3	7
17.50	96.864	2,080,800	795,240	188.1	7
20.00	94.485	2,139,840	846,720	191.9	7
22.50	108.47	2,184,120	898,200	198.0	7
25.00	91.888	2,235,960	950,040	200.0	7

Table 3 shows the results of the sensitivity analysis for ΔT_{min} using HENSAD. Hot and cold utility duty increase with increasing ΔT_{min} , indicating that it is a pinched process and can be optimized. It is observed that for a ΔT_{min} of 20 °C, the vertical heat transfer between the compound curves leads to a minimum heat transfer area of the HEN of 94.48 m² and the minimum number of units in the heat recovery system (N_{min}) that satisfies the MER requirement (without decomposing the network at the Pinch) is 7. The optimum minimum temperature difference is 5 °C for an equivalent annual operating cost (EAOC) of 172, 100 \$/y, too low for this type of process.

4.3. HEN design

Once the HEN targets have been determined, the development of the HEN design begins; being necessary to interpret several rules and principles that as a result of their implementation are satisfied by a design with a maximum heat recovery or minimum consumption of heating and cooling services [26]. Figure 4 shows the grid diagram reported by Aspen Energy Analyzer. Based on stream splitting algorithms for the combination of hot and cold streams, above and below the Pinch point, above the Pinch the number of hot streams (NH) is minor to the number of cold streams (NC) and it is found that $CPh \leq CPc$, that is, $5.74 < 8.38$. The combination of the streams H2 and C3 is feasible. Between the two Pinches, the combination H2 y C1 is feasible. The sum of E-100 and E-101 duties satisfy the MER, as shown in Figure 5a and Figure 5b. Below the Pinch there are no feasible combinations.

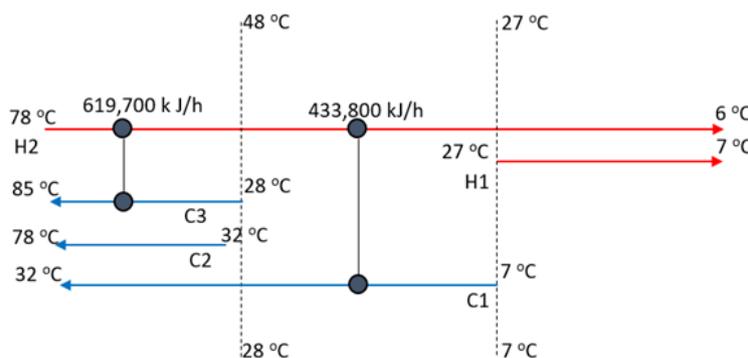
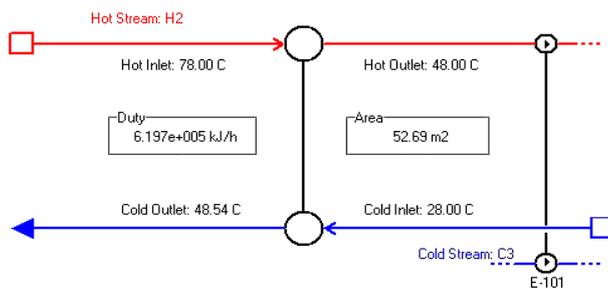


Figure 4. Network design.



(a)

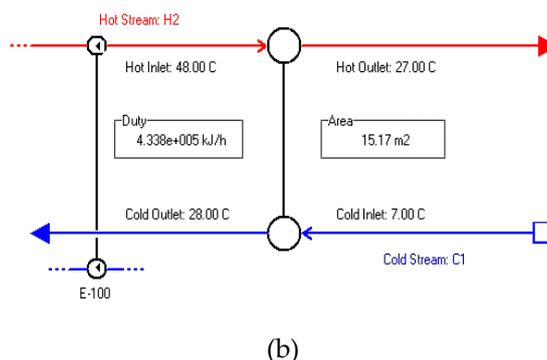


Figure 5. HEN connectivity. (a) E-101, (b) E-100

The combination of streams as shown in Figures 5a and 5b defines a heat recovery of 1,053,500 kJ/h, which equals the MER. Maximizing the energy recovery minimizes the external requirements for heating and cooling duties and minimizes the energy consumption. An investment project for two heat exchange units in the current heat exchanger network is feasible. This implies connecting the stream H2 with C3 in exchanger E-101 and then with the stream C1 in exchanger H-100, with the respective piping and control systems; which are feasible to implement in this facility.

Fuel and water quantities and financial savings are calculated from the MER.

For the economic analysis, a net calorific value of 40,600 kJ/kg for fuel, 300 d/y, 8 h/d, 720 USD / t fuel oil, 0.1USD / m³ and inlet and outlet temperatures for water (2 °C and 40 °C) were assumed.

Table 4 shows the current energy and water duties, energy targets, minimum cold utility, the energy recovery and the potential savings in energy and financial resources for the heat recovery system in the fluid milk processing plant. These energy duties represent a potential saving of 60 t/y in fuel (fuel oil) and 15,800 m³/y in water.

Financial savings in fuel and water would make it possible to assess the feasibility of the project.

Table 4. Results of the economic analysis

Duty	Energy analysis (kJ/h)	Heat Integration $\Delta T_{min} = 20\text{ }^{\circ}\text{C}$	MER (kJ/h)	Saving		
		Mínimum utility (kJ/h)		fuel oil (t/y)	water (m ³ /y)	(USD/y)
Hot (steam)	1,719,720	2,133,000	1054.2	60	-	43,420
Cold (water)	1,425,600	846,900		-	15,800	1,580
Sum						45,000

5. Conclusions

The energy analysis allowed defining the main steam and cooling water specific consumptions, until now not reported for this plant, with which an energy baseline can be defined for systematic assessment of energy performance.

Applying Pinch Analysis and HEN design allowed defining the maximum possible energy to recover and identifying opportunities to reduce fuel and water consumption, through heat exchange units in the milk pasteurization process.

Current cold utility duty is 68.33 % higher than the minimum cold utility requirement, for a minimum allowable temperature difference of 20 °C.

Determining potential annual savings of 60 t of fuel oil and 15,800 m³ of water through heat integration, allows assessing an investment project feasibility for heat recovery in the fluid milk plant.

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